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INNOVATIVE SENSOR SOLUTIONS FOR HYDROGEN: ENSURING SAFETY AND EFFICIENCY IN THE TRANSITION TO SUSTAINABLE ENERGY SYSTEMS

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White Paper

Barksdale Control Products traces our roots to 1949 when Mr. Barksdale set out to revolutionize hydraulic control in Oil & Gas applications. With a vision for precision and innovation, we pioneered the development of differentiated Shear-Seal® technology, a breakthrough that would redefine industry standards. Over the past 75 years, Barksdale has expanded its global footprint, with facilities located in Los Angeles, Germany, India and China, serving markets worldwide. Beyond our technological advancements, our story is one of unwavering commitment to our customers. From suspension systems and irrigation control to Hydrogen fuel cells and process automation, our solutions have played a vital role in shaping industries and driving growth. Today, as we embrace digital innovation, our dedication to precision and reliability remains stronger than ever. At Barksdale Control Products, we deliver engineered solutions that exceed the evolving needs of our customers, solidifying our position as a trusted partner in the Hydrogen industry.

Abstract

The hydrogen industry is poised to play a pivotal role in the global transition to sustainable energy systems. As a versatile and clean energy carrier, hydrogen offers significant advantages for applications in transportation, energy storage, industrial processes, and power generation. However, the deployment of hydrogen technologies is challenged by material compatibility issues, particularly hydrogen embrittlement and permeation, which can compromise the safety and efficiency of hydrogen storage and transportation systems. This report explores some diverse applications of hydrogen, delves into the technical problems associated with hydrogen environments, and presents two sensor solutions to address these challenges. A comparative analysis was conducted between Gold-plated piezoresistive pressure sensors and 316 L One-piece Monolithic sensors, specifically regarding performance and suitability in Hydrogen applications. This comprehensive analysis underscores the future of sensing, and the critical need for innovative materials and technologies to ensure the safe and efficient utilization of hydrogen, thereby supporting its role in a sustainable energy future.

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1 | An Introduction to Hydrogen

Hydrogen is the first element on the periodic table and the most abundant element in the universe. It is the lightest element, and plays the most crucial role in the chemistry of the universe. It is the fundamental building block of stars and galaxies, and is a major constituent of water and all organic life. In nature, it exists primarily in its diatomic form – the H₂ Gas. Due to its high energy content per unit mass and its ability to produce water when combusted, hydrogen is considered a promising clean energy carrier.

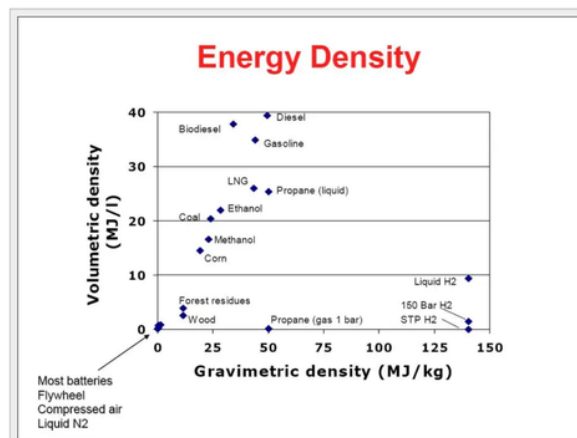
Compressed Natural Gas (CNG) and Hydrogen are both considered cleaner alternatives to traditional fossil fuels, but they differ significantly in their chemical properties and energy characteristics. For ease of understanding, we'll compare pure hydrogen to methane, which typically makes up about 90% of a natural gas mixture.

Property	Hydrogen	Natural Gas (Methane)
Chemical Formula	H ₂	CH ₄
Molecular Weight	2	16
Flammability limit (% of fuel in a fuel/air mixture that's required to ignite)	4% to 75%	7% to 20%
Flame Speed (cm/sec)	200-300	30-40
Adiabatic Flame Temperature (deg F)	4000	3565
Heating Value (Energy content per unit mass – BTU/lb)	51623	21518

As seen above, Hydrogen has a higher energy content per unit mass compared to CNG, thus offering greater energy efficiency and lower emissions of greenhouse gases and pollutants.

Overall advantages of using Hydrogen:

- Hydrogen is colorless, odorless, tasteless, and cannot usually be detected by human senses.
- It is non-toxic and non-poisonous.
- It is 14 times lighter than air, which allows it to rise very quickly (20 meters/sec) and disperse rapidly. This buoyancy serves as a built-in safety advantage in an outside environment.
- It has the highest energy content per unit mass from the prevalent options, approximately 3 times that of gasoline and >2 times that of CNG.



source:<http://www.olicognography.org/graph/energydensity>

2 | Applications

1. Transportation

- Hydrogen Fuel Cell Vehicles (FCVs): Eco-friendly cars, trucks, and buses powered by hydrogen fuel cells emit only water vapor.
- Public Transit: Hydrogen-powered buses and trains help reduce urban air pollution.
- Aviation and Shipping: Development of hydrogen-powered aircraft and ships aims to lower the carbon footprint of long-distance travel and cargo transport.

2. Industrial Processes

- Refining: Hydrogen removes sulfur from fuels, producing cleaner gasoline and diesel.
- Ammonia Production: Essential for fertilizers, the Haber-Bosch process relies on hydrogen.
- Methanol Production: Hydrogen is crucial for synthesizing methanol, a key chemical feedstock.
- Steel Manufacturing: Using hydrogen as a reducing agent can significantly lower carbon emissions in steel production.

3. Power Generation and Storage

- Hydrogen Fuel Cells: Provide clean electricity for buildings and remote locations.
- Hydrogen Turbines: Can generate electricity by burning hydrogen, alone or mixed with natural gas.
- Energy Storage: Hydrogen stores excess renewable energy for use when supply is low, addressing intermittency issues.

4. Residential and Commercial Heating

- Hydrogen Boilers: Replace natural gas boilers, offering zero carbon emissions for heating and hot water.
- Blending with Natural Gas: Gradually reduces the carbon footprint of heating systems by mixing hydrogen with natural gas.

5. Emerging and Future Applications

- Synthetic Fuels: Hydrogen can produce sustainable alternatives to fossil fuels.
- Data Centers: Hydrogen fuel cells offer a reliable backup power source.
- Space Exploration: Hydrogen is a key rocket fuel for current and future space missions.



3 | Challenges

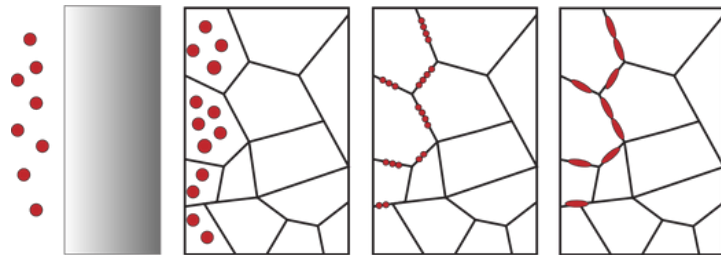
Hydrogen, despite its potential as a clean energy source, presents several challenges when used in industrial environments. It is important to understand these challenges to align engineering efforts towards R&D to come up with innovative solutions to solve these problems. These Hydrogen challenges primarily stem from its physical and chemical properties, which require careful consideration and advanced engineering solutions.

1. Hydrogen Embrittlement

Embrittlement refers to the phenomenon causing brittleness and loss of ductility in a material. Hydrogen being such a small atom, can easily penetrate through micropores and flaws in the surface of a material. Once inside, it combines with other Hydrogen atoms, and subsequently bonds with more H₂ molecules thus resulting in a mass of Hydrogen that exerts outward pressure on the material's flaws and causing subsequent cracking. Thus, Hydrogen embrittlement is a significant challenge.

- Absorption and Diffusion: Hydrogen atoms diffuse into metal structures, causing internal stresses and weakening the material.
- Stress Concentration: Hydrogen exacerbates existing defects and microcracks, leading to premature failure.
- Material Degradation: Metals like steel can suffer reduced ductility and strength, leading to increased maintenance and replacement costs.

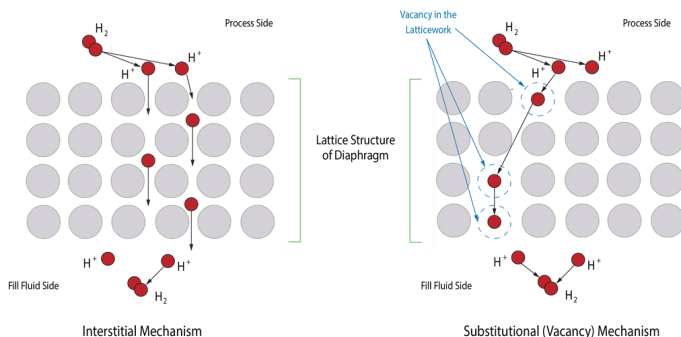
Hydrogen Embrittlement



2. Hydrogen Permeation

Hydrogen permeation involves the diffusion of hydrogen atoms through materials, leading to leakage and potential safety hazards. Hydrogen ions could penetrate through the diaphragm of a pressure sensor, and reform on the other side of the diaphragm to form Hydrogen bubbles and thus affect the accuracy of the sensor.

- Small Atomic Size: Hydrogen atoms can easily penetrate most materials, causing leaks.
- Pressure and Temperature: Higher pressures and temperatures accelerate permeation rates, complicating containment and storage.
- Material Weakening: Continuous exposure to hydrogen can degrade the integrity of materials, compromising safety and performance.



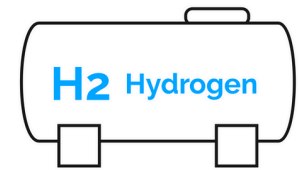
Hydrogen Permeation

Challenges

3. Storage and Transportation

Storing and transporting hydrogen safely and efficiently pose logistical and technical challenges.

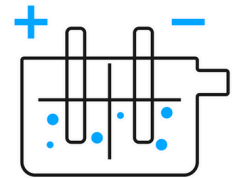
- High Pressure and Low Temperature: Hydrogen must be stored at high pressures (up to 700 bar) or low temperatures (cryogenic storage) to achieve sufficient energy density.
- Infrastructure Requirements: Developing a widespread hydrogen infrastructure requires significant investment in pipelines, storage facilities, and refueling stations.
- Safety Concerns: Hydrogen is highly flammable, and leaks can lead to explosions if not properly managed.



4. Energy Efficiency

The processes of producing, storing, and converting hydrogen involve energy losses that impact overall efficiency.

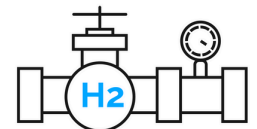
- Electrolysis: Producing hydrogen through water electrolysis is energy-intensive, and the efficiency of electrolysis systems can be relatively low.
- Compression and Liquefaction: Compressing and liquefying hydrogen for storage and transport consume additional energy, reducing the overall efficiency of hydrogen as an energy carrier.
- Fuel Cell Efficiency: While fuel cells are efficient compared to internal combustion engines, they still lose energy in the conversion process.



5. Material Compatibility

Ensuring that materials used in hydrogen environments are compatible and durable is a critical challenge.

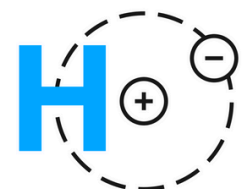
- Specialized Materials: Conventional materials often cannot withstand hydrogen's effects, requiring the use of specialized, often more expensive materials.
- Coatings and Treatments: Protective coatings and surface treatments are necessary to mitigate hydrogen embrittlement and permeation, adding complexity and cost to system design.
- Seal Integrity: Developing seals that can prevent hydrogen leaks over prolonged periods is technically challenging, especially under varying pressure and temperature conditions.



6. Safety and Regulation

Hydrogen's properties necessitate stringent safety measures and regulatory compliance.

- Leak Detection: Reliable detection systems are needed to identify and address hydrogen leaks quickly.
- Safety Protocols: Comprehensive safety protocols and training are required to handle hydrogen safely in industrial environments.
- Regulatory Compliance: Adhering to regulations and standards (e.g., ISO 11114) ensures the safe use of hydrogen but can add to the complexity and cost of implementation.





4 | Solutions

At Barksdale, we are committed to developing innovative pressure sensing solutions that are impervious to the above-mentioned challenges of dealing with Hydrogen. In this section, we will explore two different sensor technologies that curb the effects of Hydrogen embrittlement and Hydrogen permeation.



Gold-plated Sensor

Gold-plated Piezoresistive Sensors

Gold plating is an effective method to address hydrogen permeation in pressure sensors. The unique properties of gold make it an excellent barrier against hydrogen, thus protecting the diaphragm and enhancing the reliability and longevity of pressure sensors used in hydrogen environments.

Benefits of Gold Plating

1. Hydrogen Impermeability
 - Dense Structure: Gold has a dense atomic structure, which makes it highly impermeable to hydrogen atoms.
 - Low Solubility: Gold has a very low solubility for hydrogen, preventing the absorption and subsequent permeation of hydrogen atoms.
2. Corrosion Resistance
 - Chemical Stability: Gold is chemically inert and resistant to corrosion, even in harsh environments. This ensures that the sensor maintains its integrity and functionality over time.
 - Oxidation Prevention: Gold plating prevents the oxidation of the underlying metal, which can be particularly beneficial in maintaining the sensor's accuracy and longevity.
3. Durability and Reliability
 - Wear Resistance: Gold-plated surfaces are resistant to wear and degradation, which is crucial for the long-term reliability.
 - Consistent Performance: The stability and resistance to hydrogen permeation provided by gold plating ensure that the pressure sensors deliver consistent and accurate readings over their operational lifespan.

Some implementation considerations are Plating thickness, Adhesion and substrate compatibility, and Cost considerations.

One-Piece Monolithic Sensors

Another way to address vulnerabilities caused by Hydrogen, are to use One-piece sensors, furthermore referred to as Monolithic sensors. These consist of the sensor and body being made out of a single block of metal with a thick metal diaphragm, and without needing any welding. These have a variety of different benefits, including protection from embrittlement, easy installation, higher burst pressure etc. Additionally, the 316 L material exhibits excellent corrosion resistance.

Monolithic Sensor



Benefits of 316L Monolithic Sensors

1. Reduced Risk of Hydrogen Embrittlement
 - Welding can introduce vulnerabilities in materials that may be susceptible to hydrogen embrittlement. By avoiding welding, the risk of hydrogen-induced degradation is minimized, enhancing the long-term reliability of the sensor.
2. Simplified Installation
 - Welding can be a complex and time-consuming process, requiring skilled labor and specialized equipment. Using a one-piece sensor without welding simplifies the installation process, reducing labor costs and potential errors during assembly.
 - Sealing hydrogen with elastomers presents several challenges due to the unique properties of hydrogen and the limitations of elastomeric materials. Which is totally avoided by using one-piece sensor construction.
3. Enhanced Durability
 - The monolithic sensors have a 316L material diaphragm and no silicon oil filling. 316L exhibits excellent corrosion resistance, thus offering higher durability to the sensor. Welding can introduce stress concentrations and weaken the structural integrity of materials. One-piece pressure sensors without welding offer a more robust and durable solution, minimizing the risk of premature failure and downtime.
4. Compatibility with High-Pressure Environments
 - The thick diaphragm allows the sensor to perform well when it comes to rapid compression and decompression, thus allowing it to withstand higher pressures and give the sensor a higher burst pressure specification.

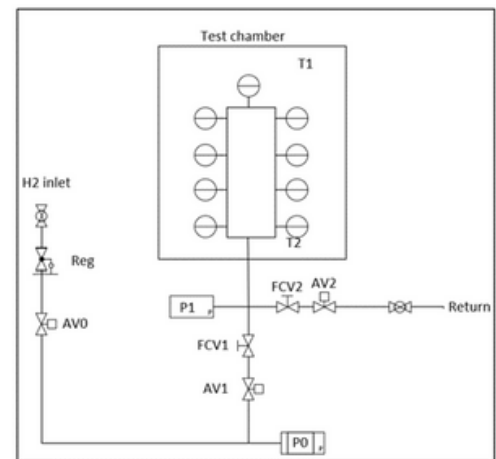
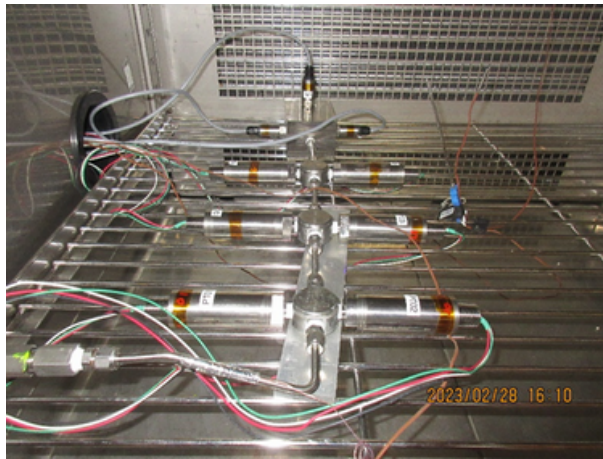


A series of tests were conducted on Silicon oil-filled piezoresistive (O), Gold-plated Silicon oil-filled Piezoresistive (G) and 316L monolithic sensors (M) to evaluate the performance of the Monolithic pressure sensor technology, as compared to the industry standard Gold-plated piezoresistive sensors.

Test 1: Comparative Endurance Test

Both types of sensors underwent a lifecycle pressure test for greater than 100K cycles at a pressure of 6500 psi (450 bar), using Hydrogen as the media. Factors such as sensitivity, response time, and long-term stability were measured using varying Pressure and Temperature conditions.

Test 1 Setup:



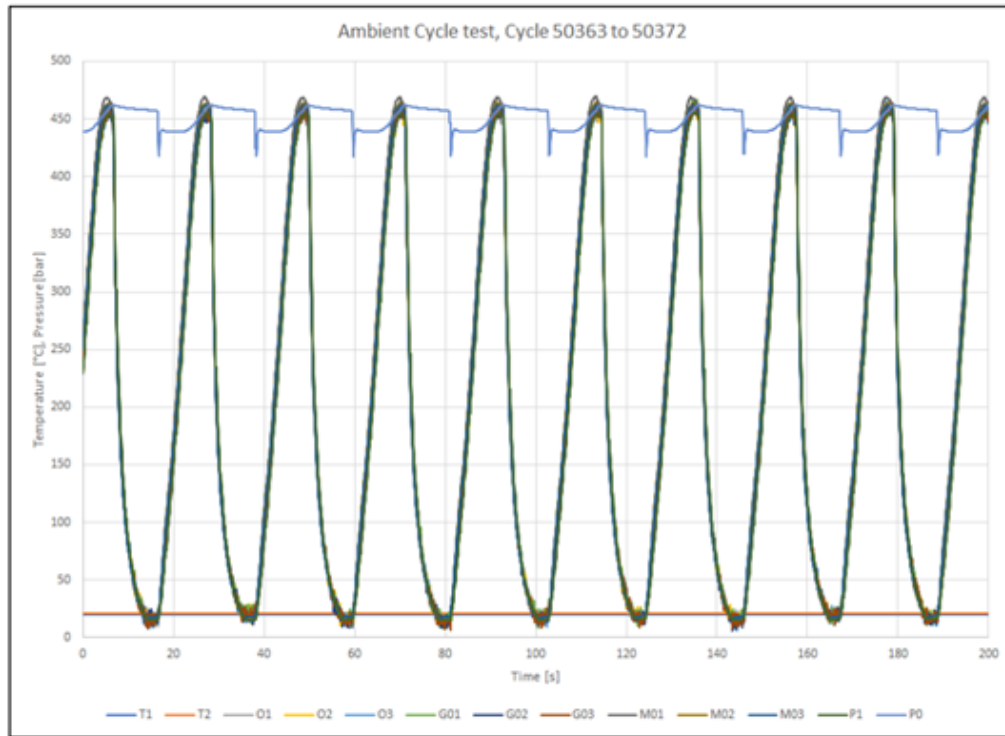
Where,

- T1 is a chamber temperature • T2 is a surface temperature on one sample
- P1 is sample pressure • P0 is inlet pressure

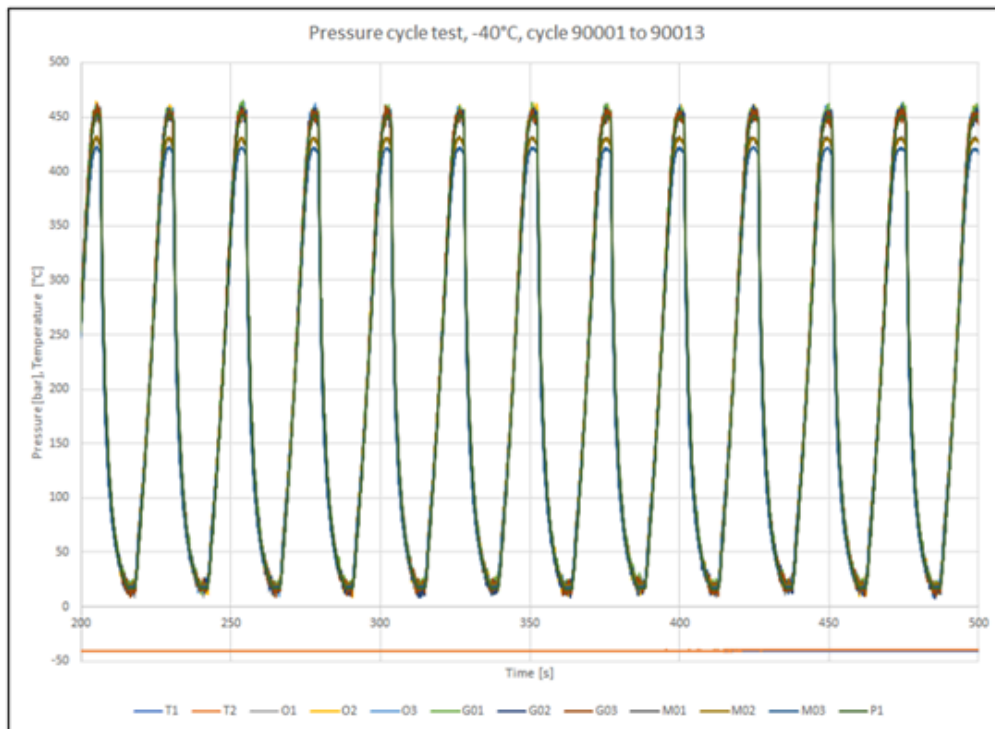
Test 1 Conditions (Comparative Endurance Test):

Three pressure sensors of each type were pressure cycled with hydrogen gas from 300 psi to 6500 psi (20 bar to 450 bar). The cycle rate was not more than 6 cycles per minute. 90% of the cycles were conducted at 20°C, 5% at -40°C and 5% at +85°C. A zero check was performed at intervals during the pressure cycle test. The samples were assembled into a manifold and were subjected to an external leakage test prior to testing, at the conclusion of testing at ambient, minimum and maximum temperature tests.

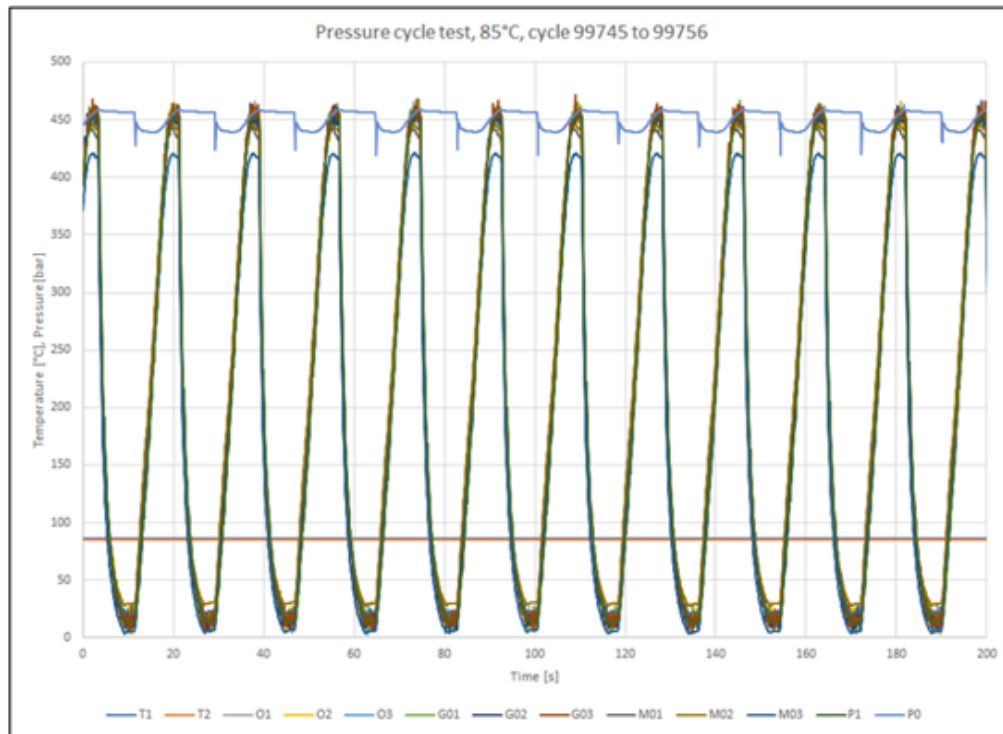
TEST 1 RESULTS



Samples displayed identical performance over 90,000 pressure cycles from 300 psi to 6500 psi (20 bar to 450 bar) at 20 degC.



Samples displayed identical performance over 5000 pressure cycles from 300 psi to 6500 psi (20 bar to 450 bar) at -40 degC.



Samples displayed identical performance over 5000 pressure cycles from 300 psi to 6500 psi (20 bar to 450 bar) at 85 degC.

The samples did not display any degradation in performance over 100,000 cycles, and hence passed the test. After the above testing was conducted, the samples were subjected to an external leakage test at 6500 psi (450 bar) conducted at 20 degC, -40 degC, and 85 degC. The test results are as follows:

Pressure (PSI)	Sensor Type	Fatigue Cycles	Leakage
6500	Gold plated Piezo-resistive	100K	Passed
	Monolithic	100K	Passed

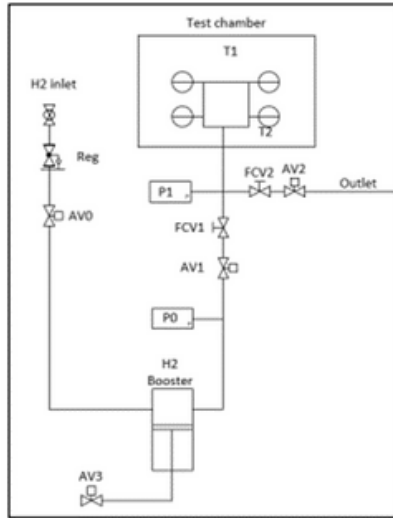
Thus, preliminary findings suggest that the Monolithic pressure sensors performed equivalently to the industry standard gold-plated piezoresistive sensors in terms of Zero offset, Linearity, and Endurance.

TEST 2 RESULTS

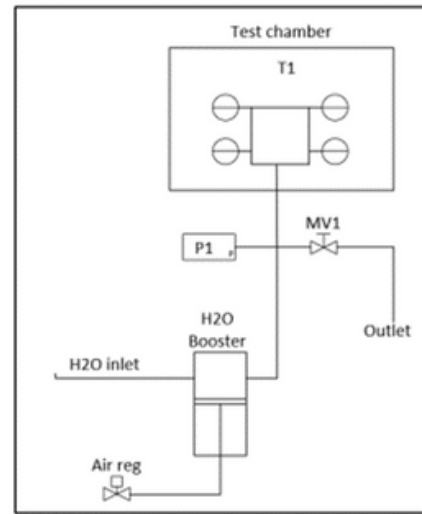
Test 2: UL 122701 Testing

Since the Monolithic sensors can withstand a higher-pressure range than the Gold-plated piezoresistive counterparts, a similar test was conducted on the Monolithic sensors at 20000 psi, with Hydrogen as the media. This test was conducted in accordance with UL 122701 Clause 6.2.3, 6.2.4 and 6.2.5. This test consisted of an Endurance test, followed by a Leakage test and a Hydrostatic Burst test.

Test 2 Setup



Test 2A: Endurance Test



Tests 2B: Leakage and 2C: Hydrostatic Test



Four sensors (S1,S2,S3,S4) pressure cycled with hydrogen gas

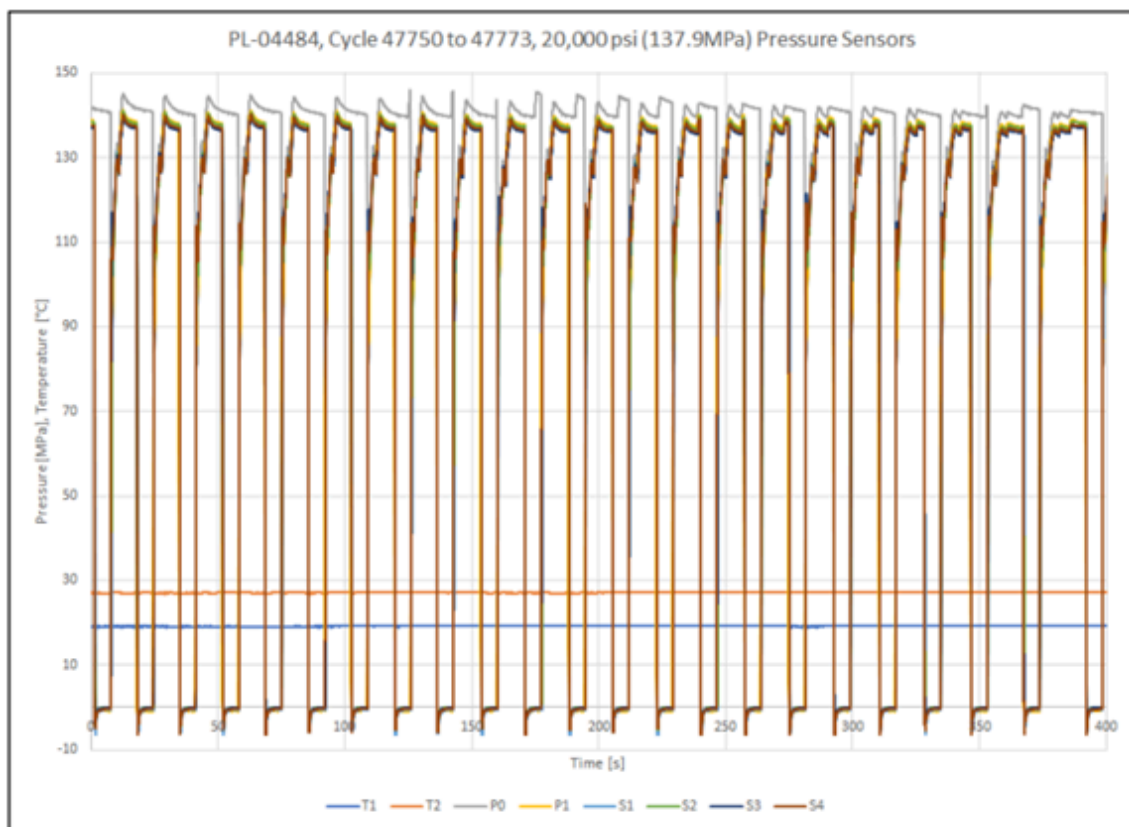
Where,

- T1 is a chamber temperature • T2 is a surface temperature on one sample
- P1 is sample pressure • P0 is inlet pressure

Test 2A Conditions (Endurance Test):

Four sensors (S1,S2,S3,S4) were pressure cycled with hydrogen gas from 0 MPa to 137.9 MPa (0 to 20000 psi). The first 10,000 cycles were held at a maximum pressure of 20000 psi for 1 minute, then depressurized to 0 psi for 1 second before being repressurized to 20000 psi. The remaining 90,000 cycles were held at 20000 psi for 5 seconds, then depressurized to 0 psi for 5 second before being repressurized to 20000 psi. All cycles were performed at an ambient temperature of 20°C.

Test 2A Results (Endurance Test):



Samples undergoing a pressure cycle test at 20 degC.

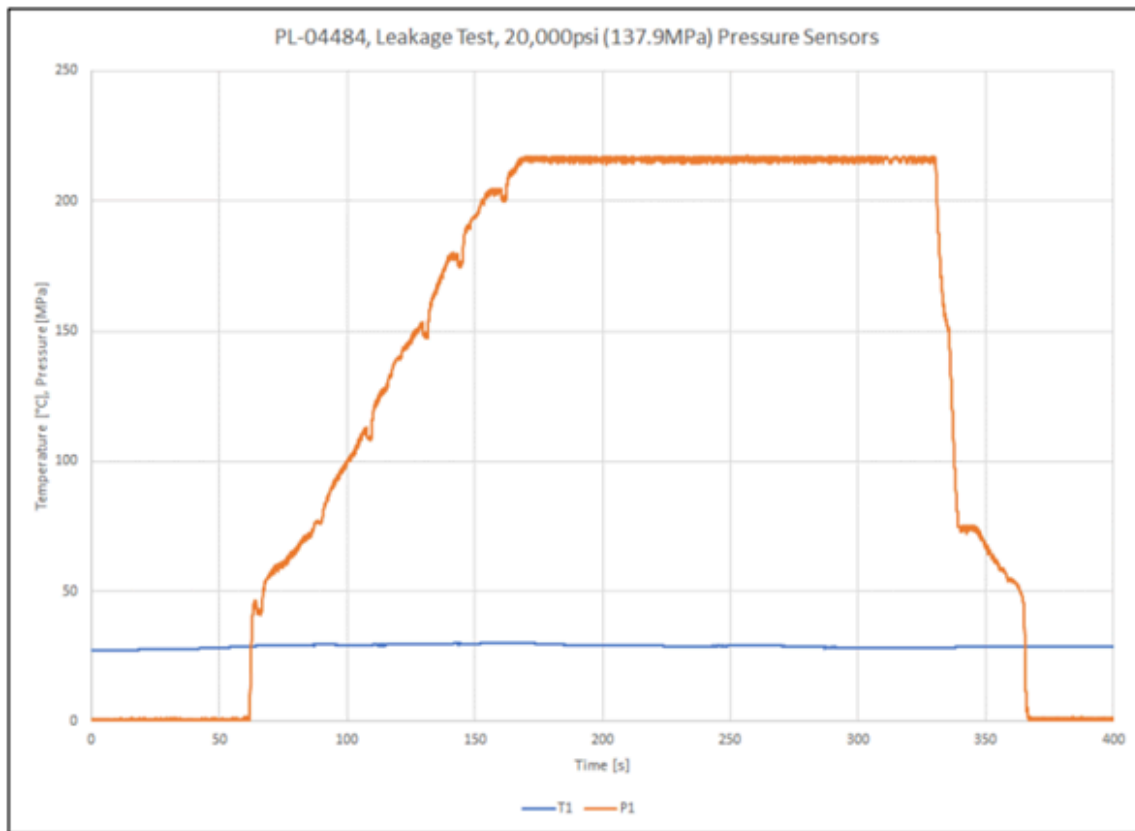
The samples did not display any degradation in performance over 100,000 cycles, and hence passed the test according to UL criteria.

TEST 2 RESULTS

Test 2B Conditions (Leakage Test):

At the conclusion of testing the samples were subjected to an external leak check using water at 214.1MPa (31,080psig), as per UL's test requirement of $1.3 \times P_{max} + 35\text{MPa}$. Prior to testing the test pressure sensor (P1) was zeroed to the atmospheric pressure for the day. The test was conducted at an ambient temperature of 20°C.

Test 2B Results (Leakage Test):



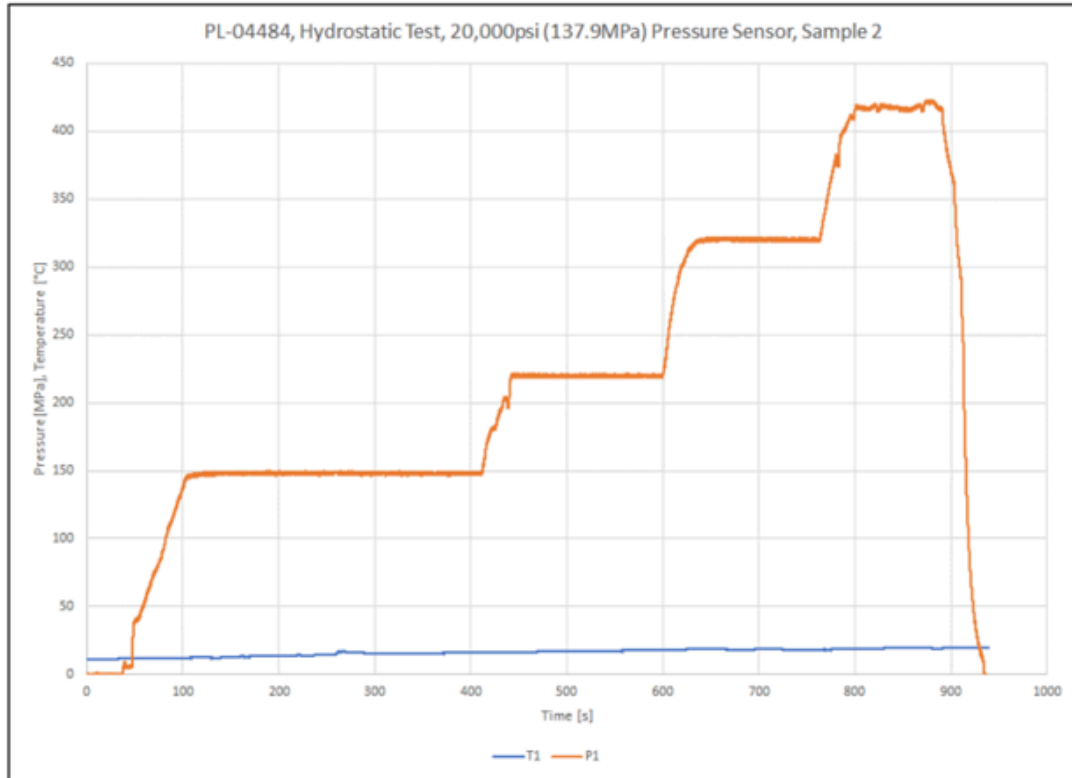
Samples undergoing a Leakage test.

All samples did not portray any external leakage after conducting the test, and hence passed the test according to UL criteria.

Test 2C Conditions (Hydrostatic Burst Test):

One sample was then subjected to a hydrostatic burst test conducted at an ambient temperature of 20°C. The burst pressure was to be more than 317.6MPa (46100psig), as per UL’s test requirement of $2xP_{max} + 42MPa$. The sample was held at 320MPa for at least one minute, then the pressure was increased to a maximum pressure of 423MPa (61350psig).

Test 2C Results (Hydrostatic Burst Test):



Samples undergoing a Hydrostatic Burst test.

All samples meet the criteria of withstanding a burst pressure greater than 317.6MPa, and hence passed the test according to UL criteria.

Overall Test 2 Results:

All Monolithic sensor samples tested met the criteria of UL 122701 Clause 6.2.3, 6.2.4 and 6.2.5 and have passed the tests.

Pressure	Sensor Type	Cycles	Result
20000	Monolithic	100K	Passed

Overall Test Results Passed

5 | Conclusion

The hydrogen industry is on the cusp of a transformative impact on the global energy landscape, offering a sustainable alternative to traditional fossil fuels. This white paper introduced the Hydrogen industry and its applications, by detailing the significant advantages of hydrogen, including its high energy content per unit mass and its potential for reducing greenhouse gas emissions. However, realizing these benefits on a large scale necessitates overcoming substantial technical challenges, such as hydrogen embrittlement and permeation, which threaten the integrity and safety of hydrogen storage and transportation systems.

Barksdale is committed to developing custom sensing solutions, that are impervious to the hazards of Hydrogen. We recently launched our new line of Hydrogen pressure sensors that employ two kinds of sensing technologies, the industry-standard Gold Plated Piezoresistive sensors, and the new 316L One-piece Monolithic sensors. Gold-plated piezoresistive sensors offer excellent resistance to hydrogen permeation due to the dense and inert nature of gold, enhancing sensor durability and accuracy. Meanwhile, 316L one-piece monolithic sensors provide robust performance with reduced risk of hydrogen embrittlement and simplified installation, thanks to their weld-free design and thick metal diaphragm.

We then conducted an experimental analysis to highlight the suitability of the Monolithic sensors in a harsh Hydrogen environment, based on the stringent UL 122701 guidelines and standards for endurance, leakage and burst testing. The experimental analysis also consisted of a comparative endurance test between the Monolithic sensors and the Gold-plated sensors, which underscored the reliability and effectiveness of both sensor technologies in Hydrogen applications, with Monolithic achieving the significant advantage of being compatible with high pressure environments with high burst pressure requirements. This makes Monolithic sensors a great solution for the pressure sensing needs of the Hydrogen industry.

In conclusion, the future of hydrogen sensing lies in the continued development and adoption of innovative materials and sensor designs. These advancements are crucial for ensuring the safe and efficient utilization of hydrogen, thereby supporting its pivotal role in the transition to a sustainable energy future. By addressing the technical challenges associated with hydrogen environments, we can unlock the full potential of hydrogen as a clean energy carrier, paving the way for a greener, more sustainable world.



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